

10 GeV dark matter candidates and cosmic-ray antiprotons

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Recent measurements performed with some direct dark matter detection experiments, *e.g.* CDMS-II and CoGENT (after DAMA/LIBRA), have unveiled a few events compatible with weakly interacting massive particles. The preferred mass range is around 10 GeV, with a quite large spin-independent cross section of 10^{-43} - 10^{-41} cm². In this paper, we recall that a light dark matter particle with dominant couplings to quarks should also generate cosmic-ray antiprotons. Taking advantage of recent works constraining the Galactic dark matter mass profile on the one hand and on cosmic-ray propagation on the other hand, we point out that considering a thermal annihilation cross section for such low mass candidates very likely results in an antiproton flux in tension with the current data, which should be taken into account in subsequent studies.

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The DAMA Collaboration has long claimed the detection of an annual modulation in their data [1, 2], which, if interpreted in terms of dark matter interaction with the detector, seems to favor weakly interacting massive particles (WIMPs) with light masses (see *e.g.* [3]). More recently, the CDMS-II [4] and CoGENT [5] Collaborations, have announced excess events in their data. Interpretations in terms of dark matter were performed in *e.g.* [6] and [7] (see also [8] for less conventional models), indicating that WIMPs with masses around 10 GeV could also explain these measurements. In Ref. [7], it was notably shown that some of the favored regions may not be compatible among each other.

Interesting constraints on such light WIMPs may actually come from colliders [9–11]. From the astrophysical point of view, the annihilation of such light WIMPs may generate high gamma-ray fluxes which are at the edge of exclusion with current measurements [12], but there are still large uncertainties coming from our incomplete knowledge of the detailed dark matter distribution, in particular in the centers of galaxies. On the Galactic scale, cosmic-ray antiprotons also provide interesting constraints [13] since predictions are less sensitive to the choice of the halo profile, but more to the local density (see *e.g.* [14]) — indeed, the relevant annihilation yield is averaged over a volume set by the diffusion scale, which of the order of a few kpc about the Earth. It was already noticed in [15] that light neutralinos with masses below 10 GeV might generate antiproton fluxes overshooting the data if the dominant annihilation proceeds into $b\bar{b}$, because the $1/m_\chi^2$ flux suppression is no longer efficient with respect to heavier WIMPs. In their analysis, these authors used a smooth cored isothermal halo profile for the dark matter distribution in the Galaxy, which was not meant to be in clean agreement with the Galactic rotation curves. Nevertheless, the largest uncertainties did actually come from propagation, notably from the relative freedom in setting the vertical extent L of the

diffusion zone. Indeed, in their minimal case of $L = 1$ kpc, at the pessimistic edge of cosmic-ray nuclei constraints [16, 17], the dark matter contribution was shown to be dramatically decreased by almost 1 order of magnitude with respect to the best-fit propagation setup.

Here we take advantage of the recent works performed (i) by Catena and Ullio [19] (CU10 hereafter) on constraining the Galactic dark matter distribution from kinematic data on the one hand, and (ii) by Putze, Derome, and Maurin [20] (PDM10 hereafter) on cosmic-ray propagation on the other hand, to improve the antiproton analysis.

CU10 notably showed that one could reach interesting constraints on the local dark matter density by using updated tracers of the Galactic dynamics, provided some initial assumptions about the dark matter profile. These assumptions can be made on well-motivated theoretical grounds, since the highest-resolution cosmological N-body simulations to date focused on Milky-Way-like galaxies now seem to converge towards similar predictions, in between an Einasto [21, 22] and an Navarro-Frenk-White [23] (NFW) profile (*e.g.* [24–26]). Using these assumptions, CU10 derived a local dark matter density of $\rho(r_\odot = 8.25 \pm 0.29 \text{ kpc}) = 0.386 \pm 0.027 \text{ GeV/cm}^3$ in the former case and of $\rho(r_\odot = 8.28 \pm 0.29 \text{ kpc}) = 0.389 \pm 0.025 \text{ GeV/cm}^3$ in the latter case. We note that these results for the local density were confirmed independently by [27], with a completely different method — these authors derived $\rho_\odot = 0.41 \pm 0.11 \text{ GeV/cm}^3$. There are still, obviously, large uncertainties with respect to the dark matter distribution in the inner kpc about the Galactic center, since either the baryons and the central black-hole may play important roles there, increasing or decreasing the inner density depending on the hypotheses [28, 29]. Nevertheless, we underline that decreasing the density in the inner kpc has much less impact on the antiproton flux predictions than on the gamma-ray flux predictions because of spatial diffusion, as it is demonstrated further below. This is strengthened by the fact that the (anti)proton propagation scale increases with energy: antiprotons are more

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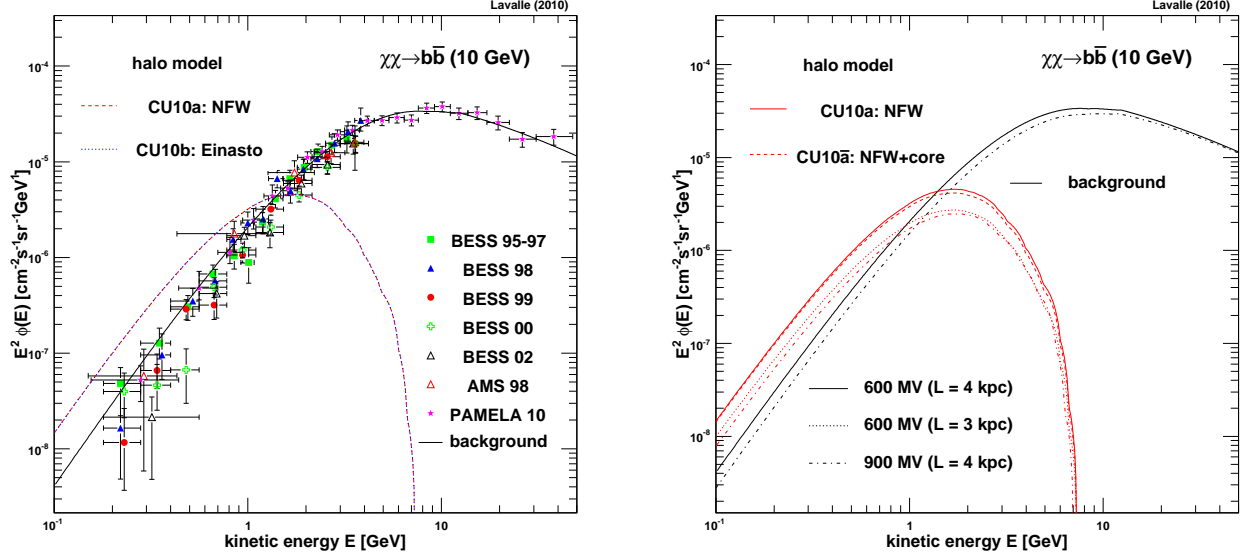


FIG. 1. Left: Predictions of the primary antiproton flux for a 10 GeV WIMP annihilating into $b\bar{b}$ pairs, for the NFW (CU10a) and the Einasto (CU10b) profiles derived in [19]. The solid black curve is the secondary background predicted using the same propagation setup [18]. Right: Impact (i) of imposing a core to the NFW case (CU10a versus CU10a-core, dashed curve), (ii) of increasing the solar modulation force field (dotted-dashed curves), and (iii) of decreasing the vertical halo boundary L from 4 to 3 kpc (dotted curve).

local if belonging to the energy range of interest here, say below 10 GeV, than those of higher energies. Typically, the propagation scale λ is set by the ratio of diffusion to convection and spallation, and is of order of a very few kpc for a 1 GeV antiproton, whatever $\lambda < L$ [30]. Otherwise, L provides an extra-limit to the propagation scale: the probability to escape the diffusion halo strongly increases for $\lambda \gtrsim L$, so that antiprotons can hardly come from regions distant by more than a very few times L .

Concerning uncertainties in the cosmic-ray propagation parameters, L , as we stressed above, has the most dramatic impact on dark matter signals. Nevertheless, the recent MCMC analysis performed by PDM10 showed that adopting a very small diffusive halo with L down to 1 kpc makes it very difficult to accommodate the current cosmic-ray nuclei data. Moreover, large diffusion halo models, as large as ~ 10 kpc, are also preferred in astrophysical studies of the high-latitude diffuse gamma-ray emission measured by Fermi [31] (see *e.g.* [32]). This minimal L of 1 kpc proposed in [14] was actually not really motivated by observational facts, but by the sake of a very conservative approach. As independent hints in this respect, it is indeed commonly observed that the radio halos of nearby spiral galaxies have sizes larger than 1 kpc (*e.g.* [33]), and a few kpc vertical extent is also favored by studies of the Galactic magnetic field (*e.g.* [34]).

In the following, we adopt the best-fit model derived in [16], which is astonishingly close to the best-fit setup derived in PDM10, in which the diffusion halo has a vertical extent of $L = 4$ kpc, still much lower than what is

suggested by the diffuse gamma-ray interpretation. We study a 10 GeV dark matter particle candidate, Majorana fermion or scalar, with a thermal annihilation cross section $\langle\sigma v\rangle = 3 \times 10^{-26} \text{cm}^3/\text{s}$, entirely annihilating into $b\bar{b}$ quark pairs — using other quark flavors would barely change the antiproton production; furthermore, taking a lower branching ratio into quarks would translate linearly into our analysis results. We have derived the injection antiproton spectrum with the public code PYTHIA [35]. For the dark matter profile, we consider the NFW and Einasto profiles constrained in CU10 and discussed above, which we respectively denote CU10a and CU10b in the following. We also investigate the potential effect of imposing a 1 kpc core to the NFW case, which we denote CU10a-core.

In Fig. 1, we show the antiproton flux predictions at the Earth obtained with the series of ingredients introduced above. We also plot the secondary antiproton background consistently derived within the *same* propagation setup [18]. The data points are taken from [36–41]. In the left panel, it clearly appears that the difference coming from using different halo profiles is negligible — at the order of a few percents, hard to see from the plot. This comes from the fact that the local normalization of the dark matter density is quite the same, and that the global shape does not differ significantly on the kpc scale around the Earth. We note that the primary contribution originating from dark matter annihilation does exceed the secondary background¹ below ~ 2 GeV, overshooting it by a factor up to almost 5 around 200

MeV. In the right panel, we illustrate the effect of imposing a core to the NFW case (CU10a, dashed curve), and demonstrate that this has a very poor impact. This is due to the limited propagation scale that characterizes the transport of low-energy antiprotons. We also study the influence of modifying the force field applied for solar modulation [42], increasing it from $\phi = 600$ MV (solid curves) to 900 MV (dotted curves). Such a change applies to both the signal and the secondary background, which makes the argument still valid in the strong solar activity regime. Finally, to allow a more conservative view, we consider a decrease of L down to 3 kpc self-consistently with the cosmic-ray nuclei constraints [18] (dotted curve) — such a change has no effect at all on the background prediction. We see that even in that case, the predicted primary flux exceeds the secondary background by a factor of 2, leading again to serious tensions with the data. We still emphasize that many independent hints favor a large diffusion halo model with $L > 3$ kpc, as already mentioned above.

Therefore, a light dark matter particle in the ~ 10 GeV mass range, annihilating into quark pairs at the thermal rate set by the relic density constraints, is expected to harden the antiproton spectrum below a few GeV. This very likely leads to important tensions with the current data. Further accounting for the predicted presence of subhalos would make this statement even slightly more severe [43], as well as considering a dark matter disk due to subhalo tidal streams trapped into the Galactic

disk [44–46]. Turning the argument around, observing a net inflexion in the antiproton spectrum around a few GeV could be a hint pointing towards the contribution of light WIMPs — it does not seem to be the case in the available data. A loophole is of course possible so as to decrease the primary signal and escape these constraints: *e.g.* combining either a lower branching ratio into quarks or a lower annihilation cross section with playing with the astrophysical parameters, or, for complete safety, taking a WIMP mass less than the (anti)proton mass [47]. Concerning the astrophysical parameters, the ongoing efforts to constrain them have started to allow for less freedom in the predictions, at least in the domain of local charged cosmic rays.

To conclude, we emphasize that light dark matter candidates considered in the interpretation of direct detection signals should be checked against the cosmic-ray antiproton data, at least whenever their couplings to quarks are significant. A more systematic study of this complementarity is on-going for different particle physics scenarios beyond the standard model and is about to show that some models are already excluded, except in contrived astrophysical situations [48].

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- ² For the non-expert reader, *secondary* means that the antiproton background comes from *secondary* astrophysical processes, namely nuclear interactions of standard cosmic-ray nuclei (mostly protons) with the interstellar gas (mostly hydrogen).

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